Active Seat Suspension for Ultra-Compact Electric Vehicle
—Fundamental Considerations on a Method for Switching Control Using Heart Rate Variability—

by

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Abstract

In the current automobile industry, the demand for ultra-compact vehicles as a means of transportation within a local area for elderly people, for example, for shopping, has been increasing. The effect of vibration of such vehicles on ride comfort is significant because of their small size and light weight, and it increases the discomfort perceived by persons in the vehicle. Moreover, ultra-compact vehicles frequently travel over alleys and unpaved roads; therefore, the ride comfort of ultra-compact vehicles is expected to deteriorate because of bumps, rough roads, and small obstacles. To solve this problem, we have proposed active seat suspension that can be installed in ultra-compact electric vehicles. Thus far, we have examined the control performance of this system and its practicality in terms of ride comfort, with the aim of reducing the vibration acceleration of the seat surface. To improve the ride comfort of vehicles, in addition to reducing the vibration acceleration of the seat surface, it is also necessary to control the vibration on the basis of the ride comfort perceived by drivers such as to reflect the mood and mental state at the time. We have already confirmed that the effect of the change in the vibration caused by the road surface during driving on the driver can be evaluated on the basis of his/her heart rate variability. In this study, we propose a method of controlling the active seat suspension by incorporating physiological information, i.e., the real-time heart rate variability, as a control parameter, and examining the effectiveness of the method.

Keywords: Active Seat Suspension, Ride Comfort, Ultra-Compact Electric Vehicle, Vital Sign, Heart Rate Variability

1. Introduction

In recent years, ultra-compact electric vehicles have been increasingly demanded because of environmental issues and the aging of the society. In June 2012, guidelines for the introduction of ultra-compact mobility were presented by the Ministry of Land, Infrastructure, Transport and Tourism, increasing the attention directed toward ultra-compact electric vehicles. Unlike conventional vehicles, ultra-compact electric vehicles may frequently be driven on poorly tended roads, such as narrow and unpaved roads. Such roads have bumps and many small obstacles, and therefore, the ride comfort of the vehicles is expected to deteriorate even when the vehicle is driven relatively slowly. To solve this problem, researchers in our laboratory have proposed an active seat suspension that can be installed in ultra-compact electric vehicles. Thus far, we have examined the reduction in the vibration acceleration of the seat surface by various control methods. In this study, we aim to realize active seat suspension control based on the ride comfort perceived by drivers.

Previous studies on the examination of fatigue and sleepiness due to prolonged driving, the ride comfort with respect to acceleration in the traveling and lateral directions, the structure of automobile seats, and seated posture have been reported. To the best of our knowledge, however, there have been no reports on the evaluation of the ride comfort relative to the vertical vibration acceleration using physiological indices and its application to the control of vehicles. We have already confirmed that the effect of the change in the vibration caused by the road surface during driving on the driver can be evaluated on the basis of his/her heart rate variability. In this study, we propose a method of controlling the active seat suspension by incorporating physiological information,
i.e., the real-time heart rate variability, as a control parameter, and examining the effectiveness of the method.

2. Heart rate variability

To examine the activity level of sympathetic and parasympathetic nerves under the control of autonomic nerves, we recorded electrocardiograms, as shown in Fig. 1. The interval between one R wave to the next R wave (RRI) was calculated from the electrocardiograms. The ride comfort perceived by the driver can be evaluated in real time by obtaining the time history of the RRI. Figure 2 shows a schematic of the method for obtaining the time history of the RRI from an electrocardiogram. The R wave refers to the greatest peak generated while blood is sent from the left ventricle to the aorta. The time history of the RRI is obtained by calculating the time interval between one R wave to the next R wave and plotting the RRI (ms) and time (s) on the ordinate and abscissa, respectively. When the RRI widens, the heart rate decreases and the line showing the time history ascends. When the RRI narrows, the heart rate increases and the line showing the time history descends. The activity state of the autonomic nervous system is evaluated from the time history of the RRI to examine the tension of the subject, i.e., to judge whether the subject is stressed or relaxed. In Fig. 2, when the RRI decreases from that in the previous time period, the heart rate increases, meaning that the sympathetic nerve is dominant and that the subject is tense and stressed. In contrast, the increase in the RRI indicates that the parasympathetic nerve is dominant and that the subject is relaxed. 9)

3. RRI-SW control

In this study, we propose the RRI switching (RRI-SW) control method in which the state of drivers is estimated from their physiological information, i.e., the change in the RRI, to switch the type of control in accordance with the estimated state.

For a basic examination, two types of controller (Controllers A and B) were prepared. Controller A performs active control in which a voice coil motor is driven so that a high performance of vibration suppression is ensured during travel over disturbances (Control A). Controller B comprises only a spring and damper and performs passive control in which no control voltage is applied (Control B). Figure 3 shows examples of the acceleration of the seat surface during travel over disturbances. The acceleration of the seat surface under Control A was lower than that under Control B, indicating a higher vibration-suppressing performance of Controller A.

Figure 4 shows a flowchart of the RRI-SW control method. The algorithm was prepared using the combination of the type of control and the change in the mean RRI so that the driver becomes relaxed and the mean RRI increases. In the analysis of the RRI, the mean RRI was calculated every minute considering that the results obtained under control are fed back in real time and that a certain range of time is required to reflect the results for the heart rate variability of the driver. In addition, the time until the effect of new control reflected in a driver’s RRI through trial and error was determined for 1 minute. Figure 5 shows the calculated mean RRI values and the switching of control. For example, when the mean RRI for 1 min while driving under Control A decreases from
that during the previous time period, it is judged that the driver feels stress and the control type is switched to Control B in the next time period. When the mean RRI during driving under Control B increases, it is judged that the driver feels relaxed under Control B and the application of Control B is continued.

4. Experimental setup and method

4.1 Experimental setup

The experiment was conducted on the Everyday COMS BASIC (Toyota Auto Body Co., Ltd.) which was a ultra-compact electric vehicle for one person with the active seat suspension which made a seat surface drive with an actuator. Figure 6 shows the ultra-compact electric vehicle used in our experiment. Figure 7 shows the active seat suspension installed into the seat of the vehicle. An aluminum plate was used for the driver’s seat, and the seat was supported by four coil springs and allowed to vibrate only in the vertical direction via linear sliders. A voice coil motor (VCM) that enables high-accuracy and high-speed control was adopted for the control actuator. The specifications of the vehicle and VCM are as Table 1.
ML826 PowerLab 2/26 (Nihon Kohden Corporation) in Fig. 8 was used for the measurement of heart rate fluctuation. In addition, the analysis system was the Heart Rate Variability from the same company. In recording electrocardiograms, it is desirable to attach electrodes to the body in a triangular arrangement, at the center of which is the heart. In this study, the National Aeronautics and Space Administration (NASA) induction method shown in Fig. 9 was adopted to stably record electrocardiograms with reduced noise during the steering operation, in which the driver is required to frequently move his arms.

Figure 10 shows the control system of the active seat suspension. Absolute displacement and velocity of the seat surface used for control were detected by the digital integration of the signals from the accelerometer, shown in the figure, using a computer. Furthermore, the current flowing through the VCM is detected. Moreover, the driver's electrocardiogram was measured and RRI was calculated in a computer. The control voltage was calculated from the measured values by a computer and a control force was generated by driving the VCM. As explained above, the active seat was supported by coil springs, a linear slider, and a VCM installed in parallel to these components.

4.2 Experimental method

In the experiment, the vehicle was equipped with the following three types of control to examine the effectiveness of the RRI-SW control method: the vehicle controlled by RRI-SW (RRI-SW vehicle), the vehicle controlled by controller A alone (Control vehicle), and the uncontrolled vehicle in which the seat and floor surfaces move in phase similarly to the seat of conventional automobiles (Without control vehicle). As shown in Fig. 11, the subject drove the vehicle with each control type for 10 min and sat and rested for 3 min before driving the vehicle with the next control type. The order of control applied to the vehicle driven was RRI-SW, Control vehicle, and Without control vehicle, but the order was not disclosed to the subject.

Driving experiments were carried out on flat roads in the Shonan Campus of Tokai University. Figure 12 shows a scene of the driving experiment. We selected roads that few other vehicles and pedestrians use to minimize the effect of the surroundings on the physiological reaction of the subject. A wavy road was prepared by placing hard rubber plates (width 30 mm, height 6 mm, length 150 mm) along the traveling direction of the vehicle, as shown in Fig. 13. When traveling on poor roads, such as alleys and unpaved roads, where the ride comfort will markedly deteriorate, ultra-compact electric vehicles, as used in this study, are expected to be driven at a relatively low speed to ensure safety and controllability,
because such vehicles have a lighter weight and a higher center of gravity than conventional small vehicles. Therefore, the traveling speed was set to approximately 5 km/h. The hard rubber plates were arranged at intervals of 320 mm so that the dominant frequency of input disturbance was 5 Hz for a vehicle traveling straight at this speed. The vibration acceleration frequency was set to 4-8 Hz, at which the ride comfort is considered to be greatly affected by vertical vibration according to ISO2631 and Janeway. The front and rear wheels were designed so that they run over the hard rubber plates at the same time. After passing over the wavy road, the driver turns the vehicle around to return to the wavy road; this is continued for 10 min, as shown in Fig. 14.

We obtained approval from the Ethics Committee for Research on Human Subjects of Tokai University. We also explained to the subject about the contents of the research and obtained signed consent (using a form approved by the Committee) from the subject who participated in this research.

5. Experimental results and discussion

The standard deviations of the acceleration of the seat surface during the 10 min drive were compared among the three vehicles, as shown in Fig. 15. The figure reveals that the RRI-SW vehicle shows the highest standard deviation of the acceleration of the seat surface. This may be because only the RRI-SW vehicle incorporates Controller B, which performs passive control.

Figure 16(a) shows a time history of control current for the RRI-SW vehicle during driving. No control force was applied from the actuator between 240 and 360 s and between 600 and 660 s because the vehicle was driven under Control B. Therefore, the control current during these periods is lower than that under Control A but not completely 0 A because of counterelectromotive force. Figure 16(b) shows a time history of control current for the Control vehicle for comparison. The control current never approaches 0 A, unlike the RRI-SW vehicle, because the acceleration of the seat surface was constantly reduced under conventional control during driving. By adopting the RRI-SW control method, the standard deviation of control current during driving decreased from 0.56 to 0.46 A, a decrease of approximately 18%.
Figure 17 shows time histories of the RRI while the subject is resting and driving (a) the RRI-SW vehicle, (b) the Control vehicle, and (c) the Without control vehicle. In the figures, the time period between 0 and 180 s represents rest and that between 180 and 780 s represents driving. To quantitatively compare the state of the driver during rest with that during driving, an index for evaluating the load on the driver (i.e., the index of reduction in driving load) is defined.

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\text{Index of reduction in driving load} = \frac{\text{Mean RRI during driving}}{\text{Mean RRI during resting}} \times 100 \% \tag{1}
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This index indicates the magnitude of the load imposed on the driver during driving relative to the state immediately before driving. When the index is close to 100%, the state of the driver is similar to that during rest. Namely, the vehicle showing a higher value of the index exerts a smaller load onto the driver and allows the driver to be relaxed.

Figure 18 shows the values of the index of reduction in driving load for each vehicle obtained from the time history of the RRI in Fig. 17. The RRI-SW vehicle shows an index greater than those for the other two vehicles, meaning that the parasympathetic nerve is dominant and that the subject is relaxed when driving the RRI-SW vehicle. Compared with the conventional method that controls only the acceleration, the proposed method was demonstrated to be effective for improving the ride comfort, although the number of subjects was one.

6. Conclusion

In this study, we monitored physiological information of the driver and aimed to incorporate the day-to-day differences in the physical condition and mood of the driver into the conventional control method. As an initial step, we proposed a method of controlling the active seat suspension by feeding back the heart rate variability of the driver and then switching the gain, and verified the effectiveness of the method. In the future, by increasing the amount of gain, we aim to establish a control method that can reflect the many moods and parameters of physical conditions of a greater number of drivers.

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References

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